

Planetary Interiors: Experimental Constraints

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Planetary Interiors: Experimental Constraints

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I. Jovian Planets

Jupiter and Saturn together contain over 400 Earth masses, most of which is hydrogen. The interiors of these giant planets are at high pressures and temperatures because of their large masses and low thermal conductivities [1,2]. Pressure and temperature in the mantle of Jupiter range up to a 300 GPa and several 1000 K and are about 4 TPa and 20,000 K at the center [3]. Hydrogen is fluid at these conditions [4]. Magnetic fields of giant planets are produced by the convective motion of electrically conducting hydrogen by dynamo action [5]. The magnetic field of Jupiter is that of an eccentric, tilted dipole with an admixture of higher-order multipoles. This field varies from 14 G at the north magnetic pole to 11 G at the south magnetic pole. Thus, while the Jovian magnetic field appears to be only slightly more irregular than that of the Earth, its magnitude and variation are ~20 and 6 times, respectively, greater than that of the magnitude of the Earth's field. These observations raise some interesting questions about Jupiter. For example, why is the magnitude of the Jovian magnetic field so large and asymmetric relative to that of Earth and is there a relatively sharp core-mantle boundary in Jupiter between a molecular mantle and monatomic core, analogous to the boundary in the Earth between the rocky mantle and Fe core?

In addition to giant hydrogen planets in this solar system, about 50 extrasolar giant planets (EGP) and Brown Dwarves have now been discovered. EGP masses are about that of Jupiter, although they range from 0.5 to 10 M_J , where M_J is the mass of Jupiter. Masses of Brown Dwarves range up to ~80 M_J . Since hydrogen has a cosmological abundance of more than 90 at.%, it is quite likely that these objects are composed almost entirely of hydrogen. The EGP HD209458b has been imaged, which gives its size, and its mass has been determined by interferometry. Its radius, mass, central pressure, and central temperature are 1.35 R_J , 0.7 M_J , 1 TPa, and 30,000 K, respectively, where R_J is the radius of Jupiter [6]. For comparison, the mass of Saturn is 0.85 M_J , and its central pressure and temperature are 2 TPa and 10,000 K. Thus, the universe has a substantial amount of mass in the form of "hot" and "cold" Jupiters.

The most important material to study with respect to giant planets is hydrogen because it has by far the greatest cosmological abundance. The most important pressures and temperatures for hydrogen experiments are pressures of 50 GPa to 1 TPa and temperatures of 1,000 to 30,000 K [7]. This is the region in which fluid hydrogen undergoes a transition from a molecular insulator to a monatomic metal.

The purpose of this section is to review the current experimental situation for hydrogen at high pressures and to describe the nature of observed metallic fluid hydrogen. Implications for Jupiter and Saturn will be discussed. Similar statements could be made about giant hydrogen planets now being discovered in other solar systems.

A. Laboratory experiments

Shock-compression experiments on liquid hydrogen access the high pressures and temperatures in Jupiter and Saturn [4]. Single and double-shock Hugoniot equation-of-state and temperature data have been obtained up to 20 and 80 GPa using a two-stage light-gas gun [8,9] and up to 300 GPa and a few 10,000 K using a large laser [10,11]. The gas-gun experiments access states in the Jovian mantle; the laser experiments access higher temperatures representative of states deeper in the Jovian core. All these measurements were performed to derive theoretical equations of state for hydrogen at conditions in the Jovian planets.

A reverberating shock wave was used to measure electrical conductivities of fluid hydrogen up to 180 GPa and 3000 K [12,13]. Fluid hydrogen achieves the minimum conductivity of a metal at 140 GPa, ninefold initial liquid-H₂ density, and 2600 K. Metallization density is defined to be that at which the electronic mobility gap E_g is reduced by pressure to $E_g \sim k_B T$, where k_B is Boltzmann's constant and T is temperature, at which point E_g is filled in by fluid disorder to produce a metallic density of states with a Fermi surface and the minimum conductivity of a metal.

The high pressures and temperatures were obtained with a two-stage gun, which accelerates an impactor up to 7 km/s. A strong shock wave is generated on impact with a holder containing liquid hydrogen at 20 K. The impact shock is split into a shock wave reverberating in hydrogen between two stiff Al₂O₃ anvils. This compression heats hydrogen quasi-isentropically to about twice its melting temperature and lasts ~ 100 ns, sufficiently long to achieve equilibrium and sufficiently short to preclude loss of hydrogen by diffusion and chemical reactions.

The measured conductivity increases four orders of magnitude in the range 93 to 140 GPa and is constant at $2000 (\Omega\text{-cm})^{-1}$ from 140 to 180 GPa. This conductivity is that of fluid monatomic Cs and Rb undergoing the same transition at 2000 K [14]. This measured value is also within a factor of 5 or

less of hydrogen conductivities calculated with: (i) minimum conductivity of a metal [15], (ii) Ziman model of a liquid metal [16], and (iii) tight-binding molecular dynamics [17]. Based on phenomenological modeling [9], at metallization this fluid is ~90 at.% H₂ and 10 at.% H with a Fermi energy of ~19 eV. On the other hand, tight-binding molecular dynamics calculations [18] indicate that protons are paired transiently and exchange on a timescale of a few molecular vibrational periods, ~10⁻¹⁴ s. Also, the kinetic, vibrational, and rotational energies of the dynamically paired protons are comparable. In this picture the dimer lifetime is extremely short (~10⁻¹⁴ s) and the fluid would appear to be monatomic. Fluid hydrogen at finite temperature undergoes a Mott transition at $D_m^{1/3} a^* = 0.30$ or 0.38, depending on whether hydrogen is assumed to be diatomic or monatomic, respectively, where D_m is the metallization density and a^* is the Bohr radius of the molecule or atom. Thus, this Mott criterion is not very sensitive to whether the metallic fluid is monatomic or diatomic. Metallization occurs at a lower pressure in the fluid than predicted for the solid probably because crystalline and orientational phase transitions in the ordered solid, which prevent metallization, do not occur in the fluid and because of many-body and structural effects.

These measurements show that electronic conduction is thermally activated in the semiconducting fluid and that the minimum conductivity of a metal, 2000 (Ω-cm)⁻¹, is reached at 140 GPa, 0.6 g/cm³ ($r_s = 1.6$), and 2600 K. That is, the Drude conductivity of free electrons in the strong-scattering Ioffe-Regel limit, in which the mean-free-path of an electron is the distance between nearest neighbors, is sufficient to explain the measured metallic conductivity. Within the experimental resolution, electrical conductivity is continuous, which suggests that density is also continuous through this transition. However, it is not yet possible to measure density in these experiments.

Metallic fluid, hydrogen is quantum in nature because the temperature (T) is much less than the Fermi temperature (T_F), $T/T_F \sim 0.01$, and because a temperature of 3000 K is comparable to the ground-state vibrational energy of the H₂ molecule [13,16]. Electrical conductivities in the semiconducting fluid provide electron excitation energies, which affect the equation of state via the absorption of internal energy at densities somewhat lower than required for metallization. Electrical conductivities of the nonmetallic fluid were measured under single-shock compression up to 20 GPa and 4600 K [19]. All the measured electrical conductivities (metallic and nonmetallic) were scaled to estimate the conductivities in Jupiter. It is these conductivities which cause the Jovian magnetic field.

At high shock pressures (>15 GPa) and temperatures, no first-order phase transition has ever been observed in any fluid. In particular, all dissociative transitions observed with equation of state measurements under

shock compression are continuous in density. This is true for both hydrogen [10] and nitrogen [20].

The pressure of the insulator-metal (IM) transition in solid hydrogen is yet to be measured. Static high-pressure experiments in a diamond anvil cell indicate that to reach the metallic state requires a pressure greater than 340 GPa [21] and the pressure required might be as large as 620 GPa [22]. These pressures are starting to exceed recent theoretical estimates of 300 to 400 GPa for a first order transition from the diatomic to the monatomic solid with an associated IM transition [23,24]. The metallic solid has not been observed in optical spectroscopy experiments in the range 190 to 290 [25-27]. Thus, there is no evidence for a first-order phase transition to a metallic state in solid hydrogen at static pressures up to ~ 300 GPa. The question still remains as to whether metallization at 0 K occurs by band overlap within an ordered diatomic solid or whether hydrogen undergoes a first-order phase transition from a diatomic to a monatomic solid, as suggested by Wigner and Huntington [28].

He is the elemental constituent of Jupiter with the second largest chemical abundance (~ 6 at.%) after hydrogen. The Hugoniot EOS of fluid He has been measured [29].

B. Implications for Jupiter

Implications for Jupiter of recent gas-gun experiments have been discussed [30-32] and are summarized here.

1. Nature of the interior

The transition from diatomic insulating H_2 to monatomic metallic H has been an important issue in Jovian modeling for decades. Some theoretical work suggested that this transition at high pressures and temperatures in the fluid, often called the plasma phase transition (PPT), is first order [33-35]. Other work suggested that this transition is continuous in pressure and temperature [36]. Depending on the model, the radius in Jupiter at which metallization occurs has ranged between 0.75 and 0.90 R_J , where R_J is the radius of Jupiter. As discussed below, shock experiments suggest that this transition is continuous and in Jupiter the minimum conductivity of a disordered fluid metal is reached at 0.90 R_J .

For purposes of discussion we assume that the path of pressure-temperature (P-T) states in Jupiter is an isentrope. It has been proposed that hydrogen in Jupiter in a certain P-T range is optically transparent to thermal radiation and, thus, interior states are not on an isentrope [37]. Nevertheless, recognizing this possibility and recognizing also that impurities might maintain the interior opaque to thermal radiation, for purposes of discussion we assume Jupiter is on an isentrope.

Assuming a continuous dissociative phase transition and using a fluid model based on our equation-of-state data, the isentrope of pure hydrogen was calculated from the surface temperature of Jupiter (165 K) and is shown in Fig. 1 [30]. The fluid model includes molecular dissociation, as suggested by measured double-shock temperatures at 80 GPa [9]. Since He is a small molecule as hydrogen, the equation of state of a mixture containing ~10 at.% He is not expected to be substantially different from that of pure hydrogen. In Fig. 1 temperature rises steeply with increasing pressure (depth in Jupiter) until molecular dissociation begins at ~40 GPa. At higher pressures up to ~200 GPa temperature varies slowly because internal energy is absorbed in dissociation. Metallization probably occurs in Jupiter at 140 GPa and 4000 K, as it does in our laboratory experiments at 140 GPa and 3000 K, because electrical conductivity is generally slowly varying with temperature in a disordered liquid metal.

A principal conclusion of shock-compression experiments is that it is very unlikely that a first-order phase transition at finite temperatures separates a molecular mantle from a monatomic core in Jupiter with an associated density discontinuity and nonmetal-metal transition. Rather, on the Jovian isentrope molecular hydrogen probably begins to dissociate at ~40 GPa and dissociation continues to completion at an estimated ~300 GPa. Metallization in Jupiter occurs at 140 GPa and ~4000 K in the middle of this complex region.

In general, the first-order plasma phase transition with its discontinuity in density probably does not exist. This statement is based simply on experience with dense fluids at extreme pressures and temperatures. Experiments to measure high densities at high temperatures in the fluid at a nonmetal-metal transition are yet to be performed. Theoretical predictions of the existence of the PPT are based on pair potentials for an assumed number of well-defined chemical species [34]. However, in this model the state at higher density is electrically conducting and, thus, many-body correlated electron effects must be taken into account, which is not done with pair potentials. Thus, while chemical equilibrium calculations suggest the PPT and quantum Monte Carlo calculations provide evidence for its existence [35], the fact that no first-order phase transition has ever been observed experimentally at 100 GPa pressures and several 1000 K suggests that the PPT does not exist. In addition Monte Carlo calculations are yet to be performed at the high density ($r_s = 1.6$) and relatively low temperature (2600 K) at which we have observed the minimum conductivity of metallic fluid hydrogen. This regime is difficult computationally because the electrons are degenerate and protons are paired into dimers, which means both electrons and protons must be treated quantum mechanically.

Given that thermodynamic transitions have been observed to be continuous, it is likely that many changes in chemical composition are also

continuous. Thus, representing a planetary interior with a relatively large number of layers is, in principle, reasonable if justified by experimental data.

2. Magnetic field

Since the Jovian magnetic field is produced by convection of conducting hydrogen, we assume that the magnitude of the field at a given radius is roughly proportional to the magnitude of the electrical conductivity at that radius. The magnitude of the electrical conductivity along the Jovian isentrope in Fig. 1 was calculated by treating hydrogen as a semiconductor below 140 GPa and as having the minimum conductivity of a metal, in this case $2000 (\Omega\text{-cm})^{-1}$, above 140 GPa [31]. The electrical conductivity of He is expected to be negligible compared to that of hydrogen in this regime. Thus, He acts as an electrically inert $\sim 10\%$ volume fraction and a 10% uncertainty in conductivity is negligible for this purpose. The results of this scaling indicate that electrical conductivity is much larger at larger planetary radii than thought previously, as illustrated in Fig. 2. The electrical conductivity reaches the minimum conductivity of a metal, $2000 (\Omega\text{-cm})^{-1}$ at $0.90 R_J$, as suggested by Smoluchowski [38] based on the first measurement of the magnetic field of Jupiter by a spacecraft. Jupiter had been thought to become metallic at a radius as small as $0.75 R_J$. Assuming that material with a conductivity as low as that in Uranus, $20 (\Omega\text{-cm})^{-1}$, contributes to the Jovian surface field, then radii out to $95\% R_J$ contribute to the surface magnetic field. Although surface magnetic fields decrease with distance from where they are produced [39], the Jovian surface magnetic field is probably not significantly lower than where the field is produced because it is generated close to the surface of the planet. Also, the asymmetry in the surface magnetic field of Jupiter might be readily observed because the magnetic field is generated close to the surface, which facilitates observation of higher-order components of the field [38].

For comparison with our experimental shock-compression data, electrical conductivities of molecular semiconducting hydrogen were calculated [31] using theoretical results available prior to our experiments; namely, the density-dependent electronic bandgaps of Friedli and Ashcroft [40] and of Min et al [41] and an isentrope of hydrogen of Saumon et al [42]. The results are curves FA and M in Fig. 2. The electrical conductivity of monatomic metallic hydrogen was calculated [33,43] at what was thought to be the core-mantle boundary of Jupiter at 300 GPa and is indicated as S in Fig. 2. The electrical conductivity is essentially constant above 140 GPa in a disordered fluid because once all the carriers and scattering mechanisms are excited and the mean free path becomes the distance between neighboring particles supplying conducting electrons, then electrical conductivity is relatively insensitive to further increase in density and temperature. That is to say, since the mean free path is the cube root of density and the density can increase by a factor of ~ 2 when all the molecules dissociate, electrical conductivity can increase only a factor of ~ 2 as the metallic fluid changes from essentially molecular to an electron-proton dense degenerate plasma. Figure

3 illustrates the change in our picture of the Jovian interior based on recent laboratory experiments.

In contrast with Jupiter, in Saturn the metallic phase of hydrogen is reached at $\sim 0.5 R_s$, where R_s is the radius of Saturn [2], much deeper in the planet than in Jupiter. The equatorial surface magnetic field of Saturn is 0.21 G [44], substantially smaller than the equatorial surface magnetic field of Jupiter. Thus, the fact that the magnetic field of Jupiter is generated close to the surface and in Saturn it is generated much deeper is consistent with the relative magnitudes of their magnetic fields. Similarly, the magnetic field of Earth is generated in the conducting Fe core, which extends only to about $0.55 R_E$, where R_E is the Earth's radius. The Earth's surface magnetic field (0.5 G) is about $\sim 1/20$ the field at the core-mantle boundary, ~ 1 mT [45]. Thus, for both Saturn and Earth a surface magnetic field of a few 0.1 G is generated at ~ 0.5 the planet's radius. The fact that the magnetic field of Earth is a factor of ~ 2 larger than that of Saturn might be caused by the fact that the electrical conductivity of Fe and its alloys at 130 GPa and ~ 3000 [46-48], conditions at the Earth's core-mantle boundary, is a factor of ~ 5 larger than the minimum conductivity of metallic fluid hydrogen at 140 GPa.

The details of magnetic field generation in Jupiter can, in principle, be calculated with a three-dimensional magnetohydrodynamics computer code [49]. Our conductivity data have been used to derive a scaling relation for electrical conductivity as a simple function of density and temperature [31] for use in such calculations. However, this relationship does not describe the entire range of densities and temperatures needed and additional electrical conductivity data are needed before a complete scaling relationship will be available for the wide range of densities and temperatures in the outer portion of Jupiter in which the major contribution to the surface magnetic field are generated.

While the He content has little effect on the magnitude of the magnetic field, the hydrogen isentrope in Fig. 1 suggests the possibility that He has an important effect on convection and, thus, on the existence of the magnetic field. The criterion for convection to occur is $(\partial T / \partial P)_S (\partial T / \partial P) > [(\partial T / \partial P)_S]^2$, where $(\partial T / \partial P)$ is the actual variation of temperature with pressure in the planet. If $(\partial T / \partial P)_S > 0$, this becomes the usual Schwarzschild criterion. Since Jupiter has a magnetic field, $(\partial T / \partial P) > 0$ and thus $(\partial T / \partial P)_S > 0$, as well. Since for pure hydrogen $(\partial T / \partial P)_S \sim 0$ and might actually be slightly negative in the region of metallization, He might be necessary to make these derivatives positive for the Jovian hydrogen-He mixture. That is, the hydrogen curve in Fig. 1 has a small negative slope over an appreciable pressure range; temperature needs to increase only a few percent for the curve in Fig. 1 to have a positive slope everywhere. Unlike hydrogen, He has no internal degrees of freedom at the densities and temperatures in the envelop of Jupiter. Thus, He has a higher temperature than hydrogen at the same pressure and density. As a result, a relatively small and uniform

concentration of He might make these derivatives positive for the hydrogen-He mixture. Higher-order components of Jupiter's magnetic field might be affected by inhibition of convection due to properties, including the isentropic T-P curve, of the continuous dissociative phase transition of hydrogen. In fact, the hydrogen T-P curve in Fig. 1 suggests the speculation that relatively small fluctuations in He content over such a giant planet might have a significant effect on convection. The Schumaker-Levy comets, which impacted onto Jupiter, indicated that while mixing is rapid, it occurs azimuthally rather than spherically. Thus, small fluctuations in chemical composition are expected because of Jupiter's huge size. The effects of interior dynamics on the magnetic field need to be explored.

II. Icy Giant Planets

The planets Uranus and Neptune are thought to have evolved from the accretion of water, ammonia, and methane [1,2]. At high pressures and temperatures these molecules react chemically to form complex mixtures. The EOSs of these mixtures are responsible for mass distributions and, hence, gravitational moments and their electrical conductivities are responsible for magnetic fields of the icy planets. The purpose of this section is to summarize dynamic high-pressure measurements of the EOSs and electrical conductivities of representative planetary fluids at representative pressures and temperatures.

Water is one of the most studied fluids at high shock pressures. Recent work includes Hugoniot EOS [50], shock temperatures [51], Raman spectroscopy [52], and electrical conductivities [50, 53]. The Hugoniot [50], shock temperatures [54], and electrical conductivities [50] of ammonia have been measured. The Hugoniot EOS [55-57], shock temperatures [54], and electrical conductivities [58] of methane and other hydrocarbons have been measured.

The mixture "synthetic Uranus" (SU) is composed of water, ammonia, and isopropanol in proportions which give near-cosmological abundance ratios of H, O, C, and N. Hugoniot data and conductivity data [59-61] and shock temperatures have been measured. Hugoniot EOS data for Su are shown in Fig. 4.

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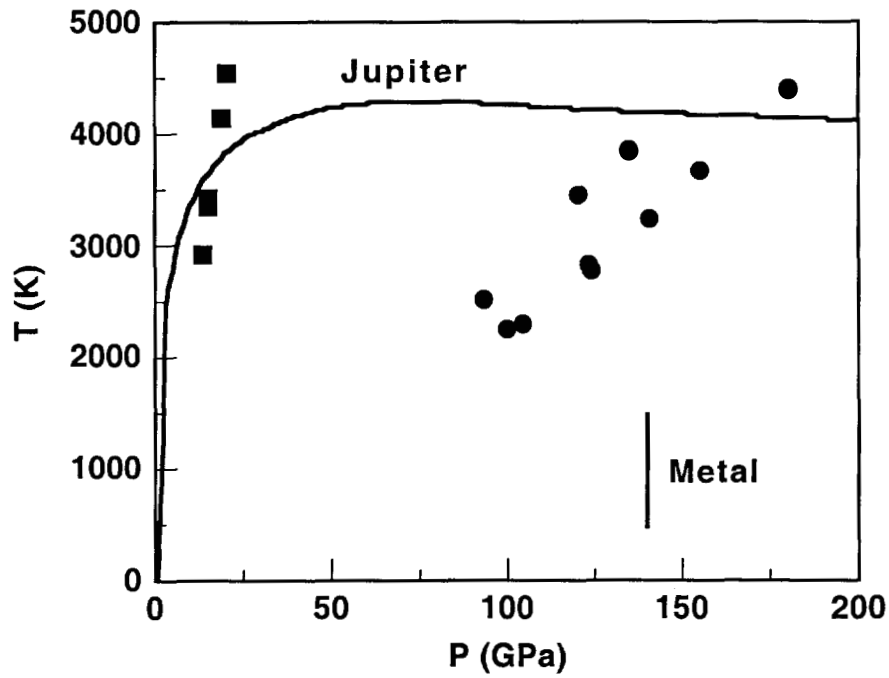


Figure 1. Solid curve is isentrope of hydrogen calculated from surface conditions of Jupiter plotted as temperature versus pressure [30]. Circles and squares represent temperatures and pressures at which electrical conductivities were measured under single-shock and multiple-shock compression, respectively [12,19]. These pressures and temperatures are representative of conditions in Jupiter. Metallization of hydrogen in Jupiter occurs at 140 GPa.

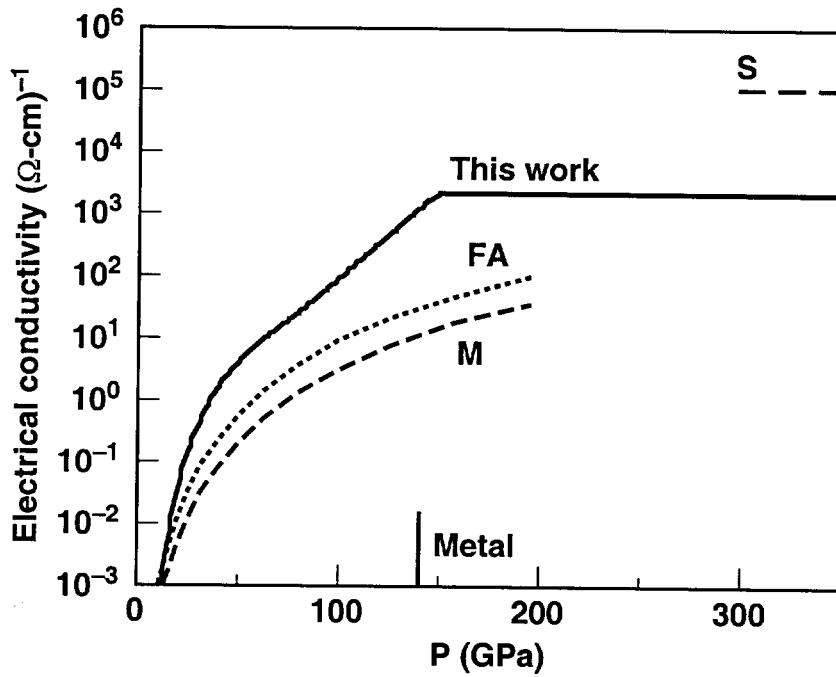


Figure 2. Electrical conductivities of hydrogen plotted versus pressure along isentropes of hydrogen with an initial temperature of 165 K calculated along the solid curve in Fig. 1 and with energy gaps FA [40] and M [41] along isentrope of Saumon et al [42]. Theoretical conductivity of monatomic metallic core S calculated by Stevenson and Salpeter [33].

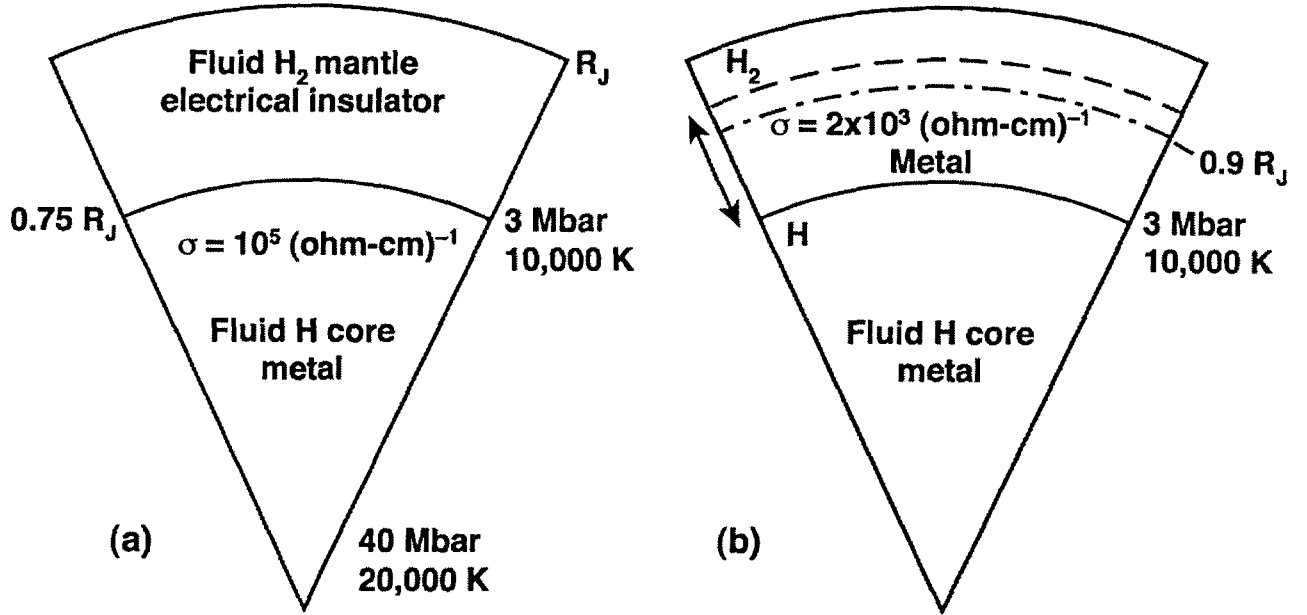


Figure 3. Schematics of our picture of Jovian interior before (a) and after (b) recent hydrogen experiments at high dynamic pressures and temperatures comparable to those in Jupiter. Previous picture in (a) has insulating molecular mantle which transitions to monatomic metallic core via first-order phase transition at $0.75 R_J$. Picture in (b) shows that H_2 is molecular down to ~ 40 GPa at $\sim 0.95 R_J$ (long-dashes), at which depth dissociation commences and is completed by $\sim 0.75 R_J$ (solid curve). Metallization occurs at a depth of at $\sim 0.90 R_J$ (dot-dashes) [31].

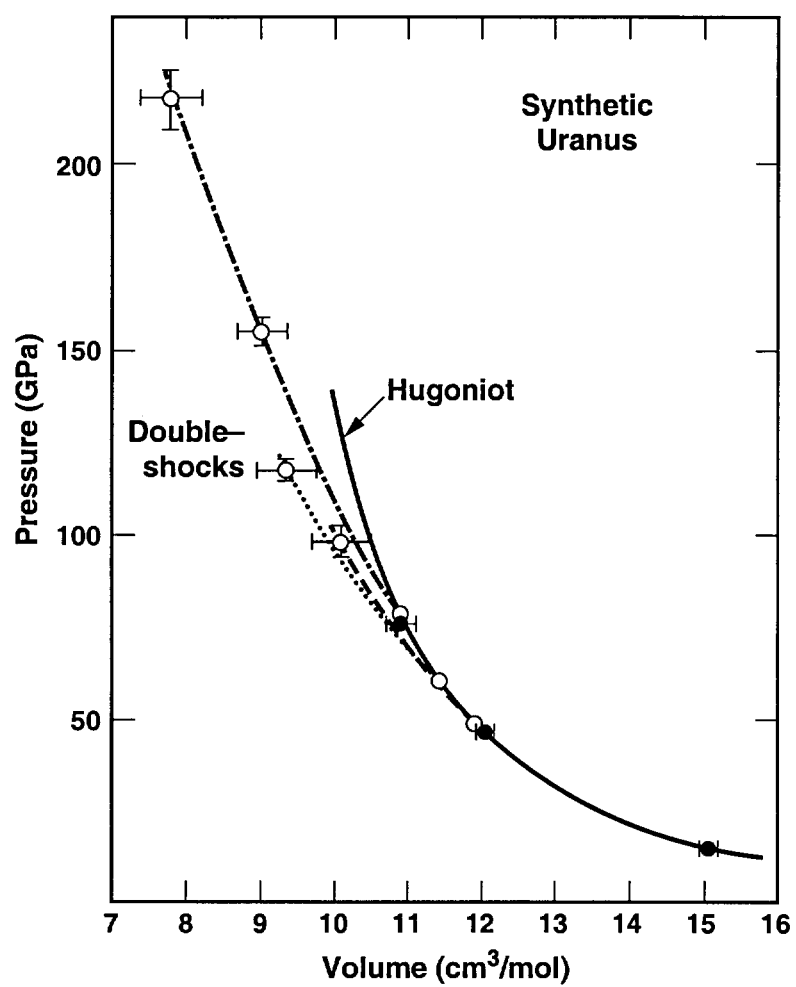


Fig. 4. Single and double-shock Hugoniot data for fluid Synthetic Uranus to 220 GPa